

A Direct Determination of the Temperature of Overheated Electrons in an Insulator

T. Levinson,^{1,*} A. Doron,¹ I. Tamir,¹ G. C. Tewari,¹ and D. Shahar¹

¹*Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel.*

Highly disordered superconductors, in the magnetic-field-driven insulating state, can show discontinuous current-voltage characteristics. Electron overheating has been shown to give a consistent description of this behavior, but there are other, more exotic, explanations including a novel, "superinsulating" state and a many-body localized state. We present AC-DC crossed-measurements, in which the application of a DC voltage is applied along our sample, while a small AC voltage is applied in the transverse direction. We varied the DC voltage and observed a simultaneous discontinuity in both AC and DC currents. We show that the inferred electron-temperature in the transverse measurement matches that in the longitudinal one, strongly supporting electron overheating as the source of observed current-voltage characteristics. Our measurement technique may be applicable as a method of probing electron overheating in many other physical systems, which show discontinuous or non-linear current-voltage characteristics.

Highly disordered superconductors can undergo a transition to an insulating state. This superconductor to insulator transition (SIT) can be driven by several parameters such as disorder strength, thickness or magnetic field (B)[1–4]. While studying the B -driven insulating state in amorphous Indium Oxide (a:InO) thin films, Sambandamurthy et al. discovered that, at low temperature (T), discontinuities appear in the current-voltage characteristics ($I - V$'s)[5]. Similar findings were later seen in disordered Titanium Nitride thin films[6], where they have been interpreted as evidence for a novel insulating state, termed a superinsulator[7].

More recently, Altshuler et al.[8] argued that the discontinuous $I - V$'s can be accounted for by electron overheating. Their theory is based on the assumptions that the electrons interact weakly with the phonons but strongly with each other, thus leading to the possibility that they will have their own, well defined T (T_{el}), which can be very different from that of the phonons (T_{ph}). Additionally, they assumed that Ohm's law holds for the entire voltage (V) range of the measurements, i.e. $V = I \cdot R(T_{el})$, where I is the current and R is the resistance. In a steady state, they could obtain T_{el} from a heat-balance eq:

$$\frac{V^2}{R(T_{el}(V))} = \Gamma \Omega * (T_{el}^\beta - T_{ph}^\beta), \quad (1)$$

Where Ω is the sample volume, Γ is the electron-phonon coupling coefficient[8, 9] and β is a material-dependent constant.

By numerically solving eq.1 for the experimentally relevant parameters, Altshuler et al.[8] found that, below a certain T_{ph} , $T_{el}(V)$ develops a bi-stable region, i.e., for a certain range of V eq.1 can have two stable solutions: A low T_{el} solution, in which $T_{el} \approx T_{ph}$, resulting in high R , and a high T_{el} solution, in which T_{el} can be much higher than T_{ph} , with much lower R . At equilibrium, ($V = 0$) the system is in the low T_{el} solution. As V is increased above a threshold value, the system enters the bi-stable region where it can spontaneously jump to the

high T_{el} solution, resulting in a discontinuous jump in I . Alongside ref.[8], Ovadia et al. conducted a detailed experimental study of the $I - V$'s, showing that they are consistent with the overheated electron framework[9].

If this framework properly describes the physics behind observed $I - V$'s, an interesting scenario emerges. At low T the application of a V can result in an analogue of the liquid to gas phase transition, but under non-equilibrium conditions[10]. The electronic system can be driven far from equilibrium, offering an experimental tool to study the nature of quantum systems under such conditions.

Despite the consistency shown by the experimental results of Ovadia et al., a direct demonstration that electron overheating is behind the reported $I - V$'s via a direct measurement of T_{el} , is still lacking. This demonstration is essential because there are other theoretical approaches that offer a distinctly different view of the discontinuous $I - V$'s in our, and in others', systems[5, 6, 9, 11–15]. One such theory is that the low I branch of the experimental $I - V$'s is evidence of a "superinsulating" state which is destroyed at a critical V [7], dual to the critical I in a superconductor. Another competing theory is that the observed $I - V$'s are a manifestation of a novel many-body localized state, as explained in ref.[16]. A third possible explanation is that application of an electric field (E) tilts the random potential created by disorder until, at a threshold E value, a conduction channel connecting the two ends of the sample forms. This model was treated in ref.[17] in the context of metallic islands in a disordered potential. It was used in order to explain discontinuous and non-linear $I - V$'s observed in various systems[11–13, 15], including insulating films[15].

We considered electronic noise measurements as a possible method to directly measure T_{el} . These measurements, an obvious option because equilibrium noise is a commonly used thermometer, proved unfeasible. The combination of low T_{el} (≈ 50 mK), high R (typically $> 10^8 \Omega$) and the need to flow a DC I while conducting the measurement, is yet too challenging experimentally.

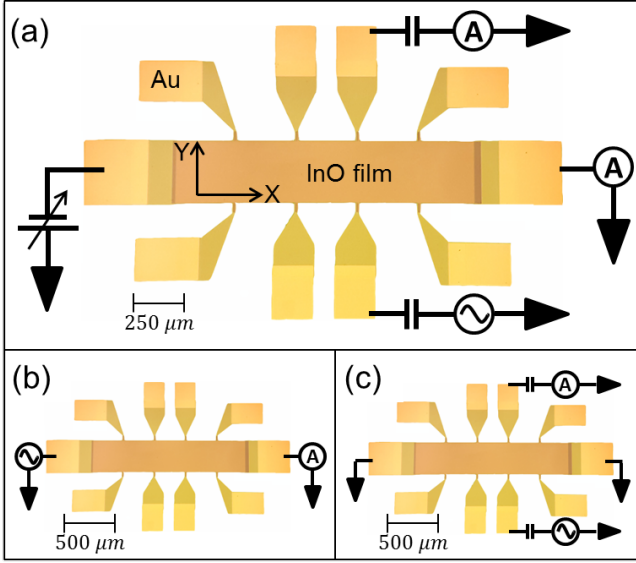


FIG. 1. **Our experimental setup.** **a.** shows the setup we used to measure $I_{X,Y}(V_X)$ (for more information see supplementary). The electronic circuit shown schematically was comprised of two trans-impedance amplifiers, a Lock-in amplifier, a DC V -source and two $10\mu\text{F}$ capacitors used as DC-blocks. **b.** shows the setup we used to measure $R_X|_{V=0}(T)$. **c.** shows the AC-equivalent electronic circuit of the full experimental setup, which is the setup we used to measure $R_Y|_{V=0}(T)$.

In this letter we have taken a different approach: According to ref.[8], R is determined by T_{el} that, in turn, is determined by the power input into the system via Joule heating. Under the assumption that Joule heating is uniform, T_{el} is also expected to be uniform throughout the system. As a result, T_{el} , as inferred by a measurement of R in a given orientation, should be the same regardless of the direction in which V is applied. The crux of our method was to sweep V and infer T_{el} from two independent measurements of R , one in the direction parallel to V and another in a perpendicular direction.

It is important to note that our method cannot directly distinguish between the scenario described above, where T_{el} differs from T_{ph} , which in turn remains equal to the T of the external bath (T_B), and a scenario where the entire sample decouples from the external bath, i.e. $T_{el} = T_{ph} \neq T_B$. In order to distinguish between these two scenarios we conducted a test experiment, whose details we describe in the supplementary materials section of this paper, which clearly indicates that the first scenario is the relevant one in our system.

The results presented in this work were obtained from a $1500\mu\text{m}$ long, $300\mu\text{m}$ wide, 10 contact Hall-bar sample of 30nm thick a:InO (see fig.1). The critical B (B_c) at which our sample showed a SIT was 0.009 T . A DC V was applied in the longitudinal (X) direction while a small, $50\mu\text{V}_{RMS}$ AC, V was applied in the transverse

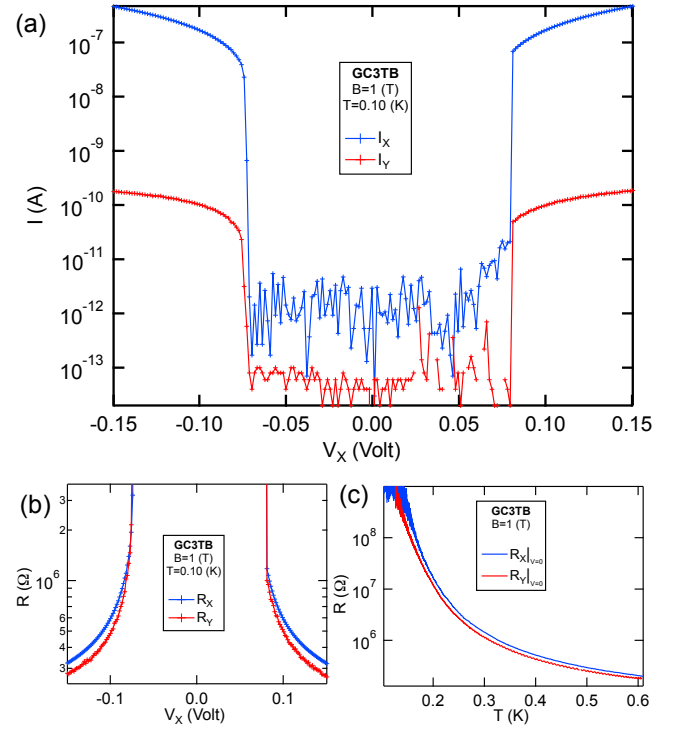


FIG. 2. **a.** I_X and I_Y vs V_X . While V_X was swept, a constant $V_Y = 50\text{ mV}$ (RMS) was applied and I_X, I_Y were simultaneously measured. **b.** R_X and R_Y vs V_X , calculated from the data shown in sub-fig. **a.** **c.** $R_X|_{V=0}(T)$ and $R_Y|_{V=0}(T)$ vs T . All sub-figures are plotted on a semi-log scale. The data were measured at $B = 1\text{ T}$, the data in sub-figs. **a** and **b** were taken at $T = 100\text{ mK}$.

(Y) direction (see supplementary information for more details). The longitudinal V (V_X) was swept from -150 to 150 mV , while the transverse V (V_Y) was held constant. During this, the longitudinal DC I (I_X) and the transverse AC I (I_Y) were measured.

I_X and I_Y vs V_X are shown in fig.2a. At low V_X both I_X and I_Y are within the noise. As V_X is increased, at $V_X \approx 80\text{ mV}$, I_X and I_Y each attain a value that appears abruptly, well above the noise, and grows progressively as V_X is increased further. Upon reducing V_X (Going from -150 to 0 mV), I_X and I_Y decrease gradually, until rapidly dropping at $V_X \approx 72.5\text{ mV}$.

Following the assumptions stated above, we calculated the longitudinal and transverse R 's (R_X and R_Y) by applying Ohm's law: $R_{X,Y} = V_{X,Y}/I_{X,Y}$. In fig.2b, R_X and R_Y are plotted against V_X , showing the same abrupt escape from the noise as seen for the I 's. The maximum R that we could measure, given our noise level in this setup, was $\approx 10^8\ \Omega$.

In order to infer a value of T_{el} from each of the data points, we used the zero-bias $R(T)$ of the sample ($R|_{V=0}(T)$), where T refers to the cryostat temperature. We conducted a two-terminal measurement of $R|_{V=0}(T)$, while sweeping T slowly (in order to ensure

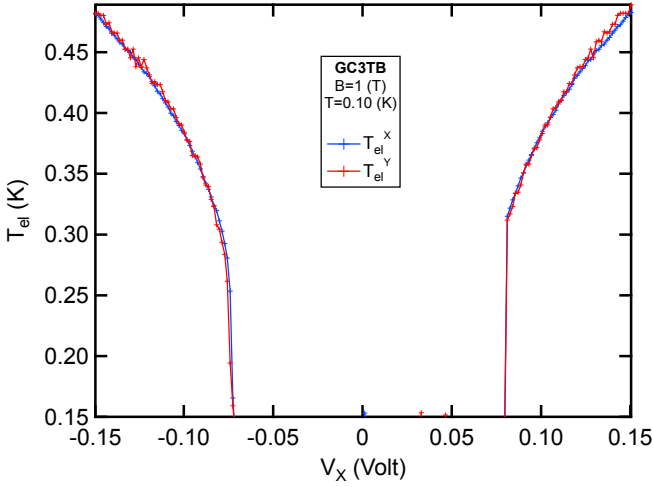


FIG. 3. T_{el}^X and T_{el}^Y vs V_X , plotted on a linear scale. $T_{el}^{X,Y}$ were calculated from $R_{X,Y}$ and $R_{X,Y}|_{V=0}(T)$ plotted in fig.2. Our experimental error did not allow us to infer a T_{el} value of below 150 mK in a reliable way, thus no data points appear below this value.

$T_{ph} = T$). At low V the $I - V$'s were linear, as was verified by $I - V$ measurements (see supplementary), indicating that $T_{el} = T_{ph}$. Thus by measuring in the linear range we ensured $R|_{V=0}(T) = R(T_{el})$.

We measured $R|_{V=0}(T)$ in two different setups. The first was the setup, shown in fig.1b, which we used to measure $R_X|_{V=0}(T)$, and the second was the AC-equivalent of our experimental setup, shown in fig.1c, which we used to measure $R_Y|_{V=0}(T)$. In both cases we used an AC V of $50\mu V_{RMS}$ which is well within the linear $I - V$ range. $R_X|_{V=0}$ and $R_Y|_{V=0}$ vs T are shown in fig.2b.

We inverted $R_{X,Y}|_{V=0}(T)$, attained $T_{el}^{X,Y} \equiv T_{el}(R_{X,Y})$ and inferred a T_{el} value from each data point of $R_{X,Y}(V_X)$. In fig.3 we plotted T_{el}^X and T_{el}^Y vs V_X . Our experimental error in $R_{X,Y}$ allowed us to measure T_{el} down to 150 mK. The agreement between T_{el}^X and T_{el}^Y is near-perfect.

We next turned our focus to a B -dependent study of the $I - V$'s using our new technique. We defined $\Delta T_{el} \equiv T_{el}^X - T_{el}^Y$. In fig.4 we plotted $\frac{\Delta T_{el}}{T_{el}^X}$ vs T_{el}^X for various B 's ranging from 0.0382 up to 12 T. For sake of clarity we only displayed a portion of the B 's that were studied, which represents the trend observed for all B 's examined. For $B > 0.15$ T, all measured T_{el}^X were within 5% of T_{el}^Y i.e. below the dashed line in fig.4. For $B < 0.15$ T, as B approached B_c , T_{el}^X became systematically larger than T_{el}^Y . Both noise and systematic error in $T_{el}^{X,Y}$ grew significantly as B approached B_c . This is due to $R(T_{el})$ becoming a progressively slow-varying function of T_{el} , thus inverting it caused large uncertainty. Nevertheless, our measurements point to a possible deviation from the overheated electron picture as B_c is approached.

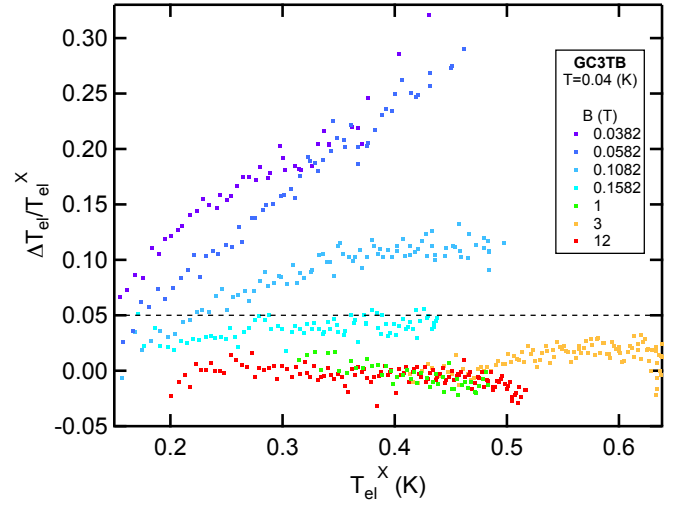


FIG. 4. $\frac{\Delta T_{el}}{T_{el}^X}$ vs T_{el}^X , plotted on a linear scale. The dashed line represents $\frac{\Delta T_{el}}{T_{el}^X} = 5\%$. The color-scale represent the B corresponding to each data set. All data were calculated from measurements conducted at $T = 40$ mK and from $R_{X,Y}|_{V=0}(T)$ similar to those plotted in fig.2.

The main conclusion of our work stems from the near-perfect agreement between T_{el}^X and T_{el}^Y , which strongly supports the theory of electron overheating as the cause of observed $I - V$'s in the B -driven insulating state displayed by disordered films. We identified a possible deviation from the overheated electron framework in the vicinity of B_c , requiring further investigation. We demonstrated a novel, simple technique to measure electronic temperature of systems which exhibit non-linear $I - V$'s. Many condensed matter systems such as Anderson-Mott insulators[15], semiconductor Quantum dot arrays[11, 12], metallic island arrays[13] and transport through constrictions[14] exhibit similar $I - V$'s. Applying our technique to these systems may serve to enhance our understanding of them, and show whether electron overheating is involved in the non-linear $I - V$'s observed in these systems.

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* Levinsontal@Gmail.com.; Corresponding author

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